

The Road to Environmentally Responsible Energy Security

Keynote Lecture – GFEECC 2015

Mohamed Abdou

Distinguished Professor of Engineering and Applied Science (UCLA)

Director, Center for Energy Science & Technology (UCLA)

Founding President, Council of Energy Research and Education Leaders, CEREL (USA)

The Road to Environmentally Responsible Energy Security

OUTLINE

1. The World Energy Situation

- Need for more energy, dominance of fossil fuels, impact on the environment, energy-water nexus

2. Renewable Energy Sources

- Solar, wind, geothermal, biomass, hydro, etc.

3. Nuclear Fission

- Existing plants, and contribution to current world energy needs
- Nuclear future outlook

4. Fusion

- Incentives to fusion
- Approaches to fusion and DEMO goal
- Current Progress AND when can we have fusion?

5. Closing Remarks

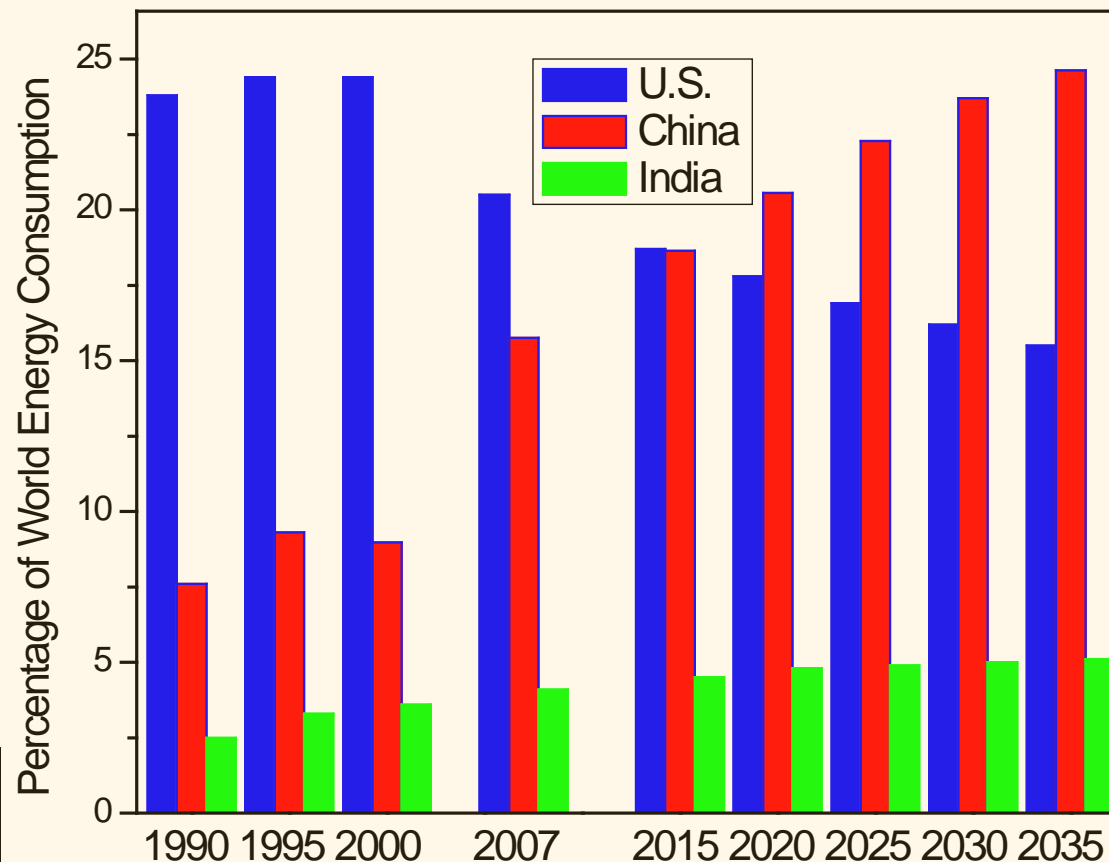
World Energy Situation

Energy Situation

- **The world uses a lot of energy**
 - Average power consumption = 17.7 TW (2.5 KW per person)
 - World energy market ~ \$3 trillion / yr (electricity ~ \$1 trillion / yr)
- **The world energy use is growing**
 - To lift people out of poverty, to improve standard of living, and to meet population growth
- **Climate change and debilitating pollution concerns are on the rise**
 - 80% of energy is generated by fossil fuels
 - CO₂ emission is increasing at an alarming rate
- **Oil supplies are uncertain**
 - Special problem for transportation sector (need alternative fuel)

Total Projected Energy Use for Selected Countries

China energy use has been rising faster than anticipated

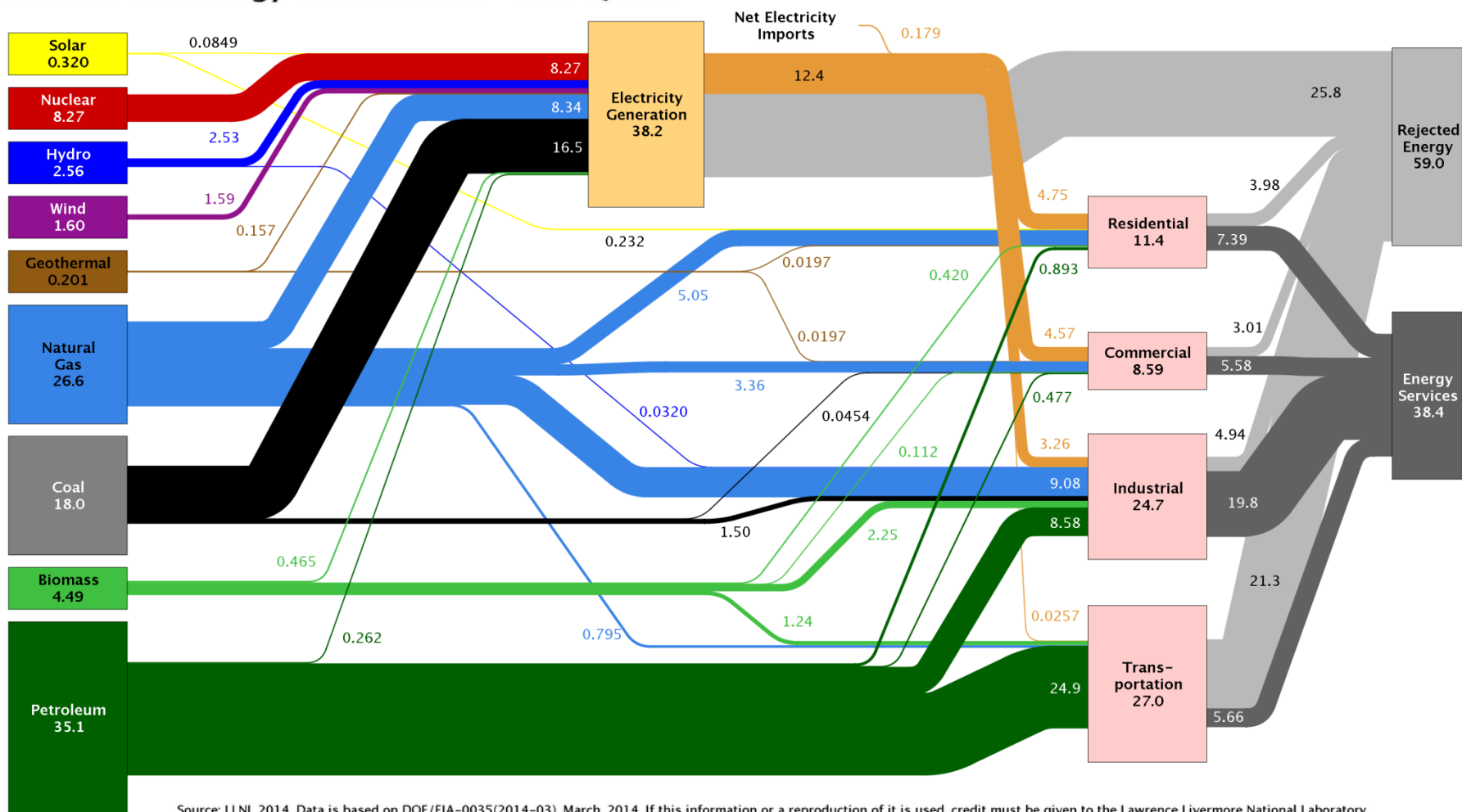


Source: Energy Information Administration, International Energy Outlook 2010

Energy Flows in the U.S. Economy, 2013

Estimated U.S. Energy Use in 2013: ~97.4 Quads

(Quadrillions of Btus)



Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

BTU Content of Common Energy Units

1 Quad = 1,000,000,000,000,000 Btu

1 barrel of crude oil = 5,800,000 Btu

1 gallon of gasoline = 124,000 Btu

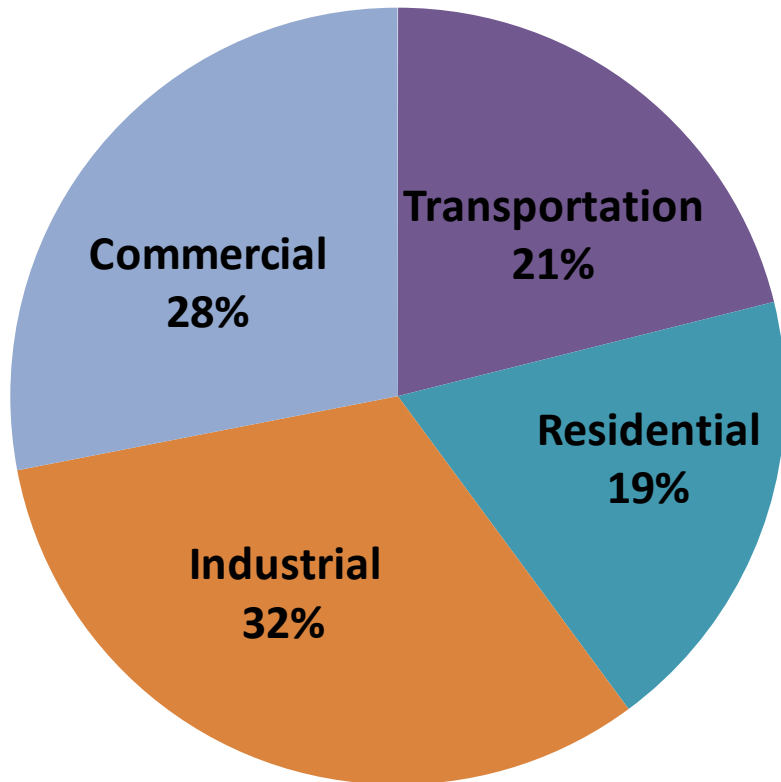
1 cubic foot of natural gas = 1,028 Btu

1 short ton of coal = 20,169,000 Btu

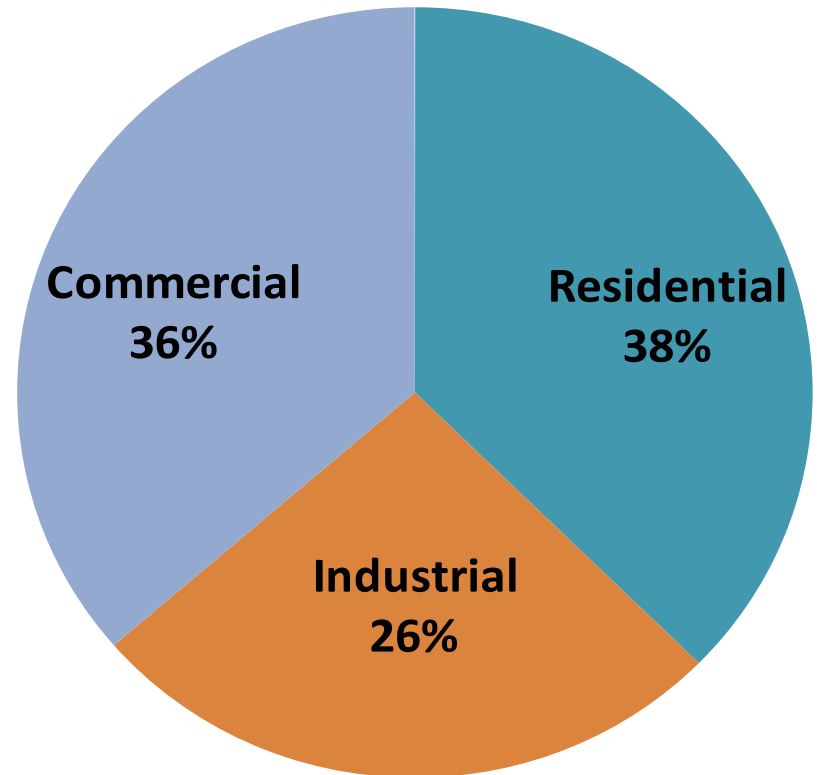
1 kilowatthour of electricity = 3,412 Btu

Energy Use by Sector (2013)

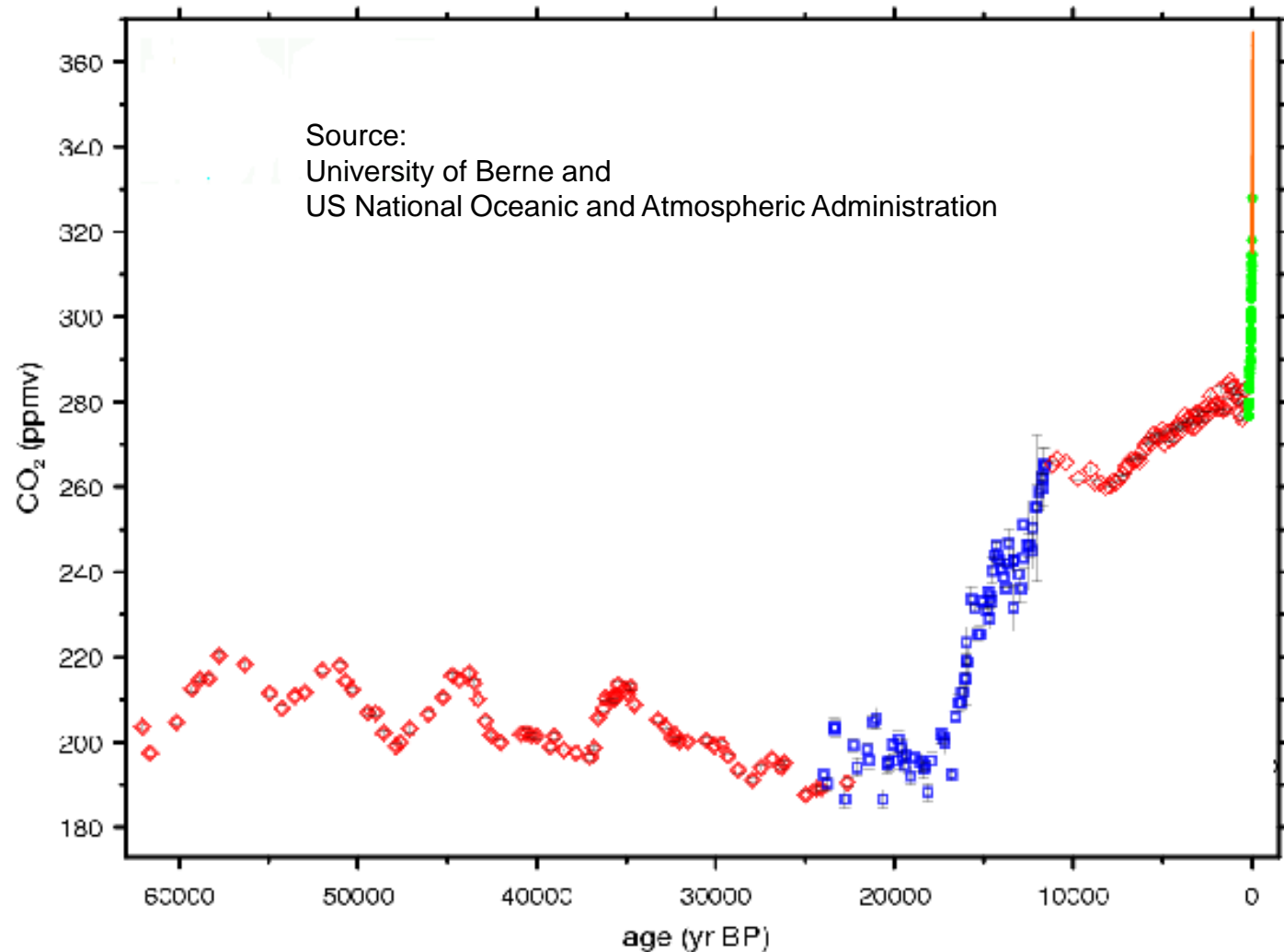
Total Energy



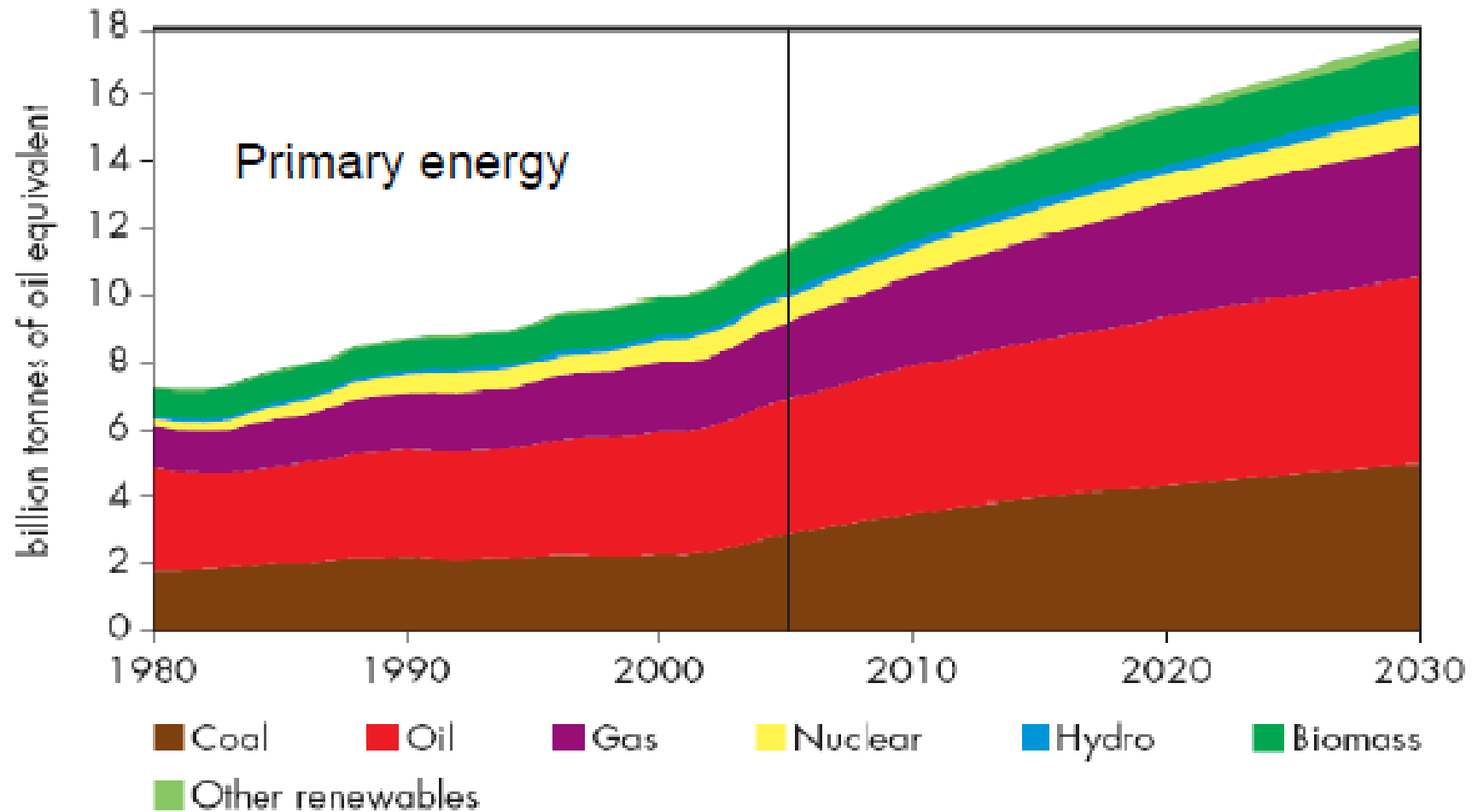
Electricity



Carbon dioxide levels over the last 60,000 years – we are provoking the atmosphere!



Where we're headed under BAU: by 2030, energy +60%, electricity +75%, continued fossil dominance



WEO 2007

**What is problematic
about this future ?**

The problem is not “running out” of energy

Some mid-range estimates of world energy resources. Units are terawatt-years (TWy). Current world energy use is ~17.7 TWy/year.

OIL & GAS, CONVENTIONAL	1,000
UNCONVENTIONAL OIL & GAS (excluding clathrates)	2,000
COAL	5,000
METHANE CLATHRATES	20,000
OIL SHALE	30,000
URANIUM in conventional reactors	2,000
...in breeder reactors	2,000,000
FUSION (if the technology succeeds)	250,000,000,000
RENEWABLE ENERGY (available energy <u>per year</u>)	
Sunlight on land	30,000
Energy in the wind	2,000
Energy captured by photosynthesis	120

Real problems: the economic, environmental, and security risks of fossil-fuel dependence

- Coal burning for electricity & industry and oil burning in vehicles are main sources of severe urban and regional air **pollution** – SO_x , NO_x , hydrocarbons, soot – with big impacts on public health, acid precipitation.
- Emissions of CO_2 from *all* fossil-fuel burning are largest driver of **global climate disruption**, already associated with increasing harm to human well-being and rapidly becoming more severe.
- Increasing dependence on imported oil & natural gas means economic vulnerability, as well as international tensions and potential for conflict over access & terms.

Real problems: Alternatives to conventional fossil fuels all have liabilities & limitations

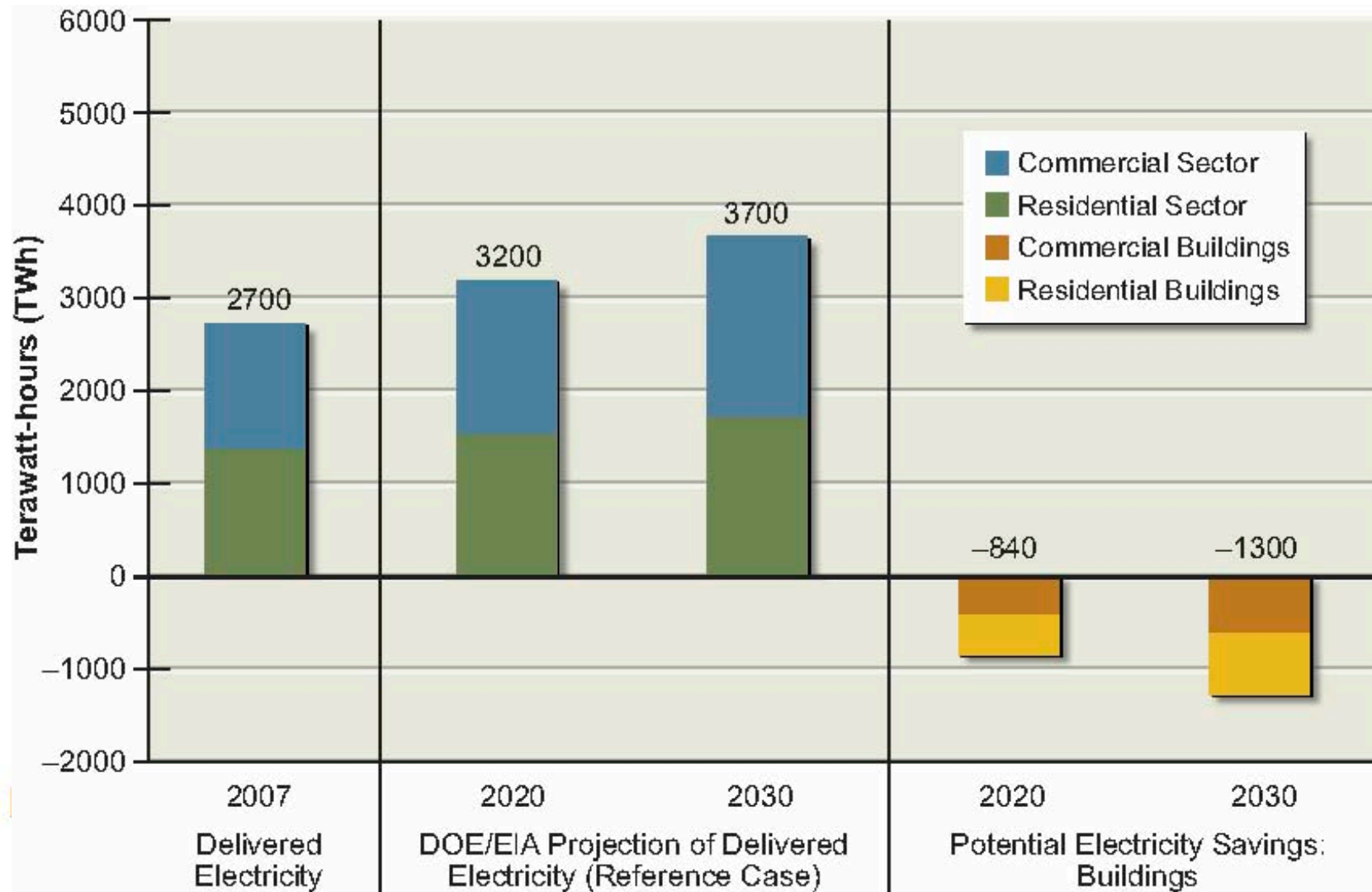
- Traditional biofuels (fuelwood, charcoal, crop wastes, dung) create huge indoor air-pollution hazard
- Industrial biofuels (ethanol, biodiesel) can take land from forests & food production, increase food prices
- Hydropower and wind are limited by availability of suitable locations, conflicts over siting
- Solar energy is costly and intermittent
- Nuclear fission has large requirements for capital & highly trained personnel, currently lacks agreed solutions for radioactive waste & links to nuclear weaponry
- Nuclear fusion doesn't work yet
- Coal-to-gas and coal-to-liquids to reduce oil & gas imports doubles CO₂ emissions per GJ of delivered fuel
- Increasing end-use efficiency needs consumer education

Solving the Energy Problem and Reducing Greenhouse Gas Emission Requires Pursuing a Diversified Portfolio Approach

- Improve energy **efficiency**
- Expand use of **existing** “clean” energy sources (e.g. **nuclear and renewable sources – solar, wind, etc.**)
- Develop technologies to **reduce impact of fossil fuels** use (e.g. carbon capture and sequestration)
- Develop major **new** (clean) energy sources (e.g. **fusion**)
- Develop **alternate (synthetic) fuels** and electrical energy storage for transportation

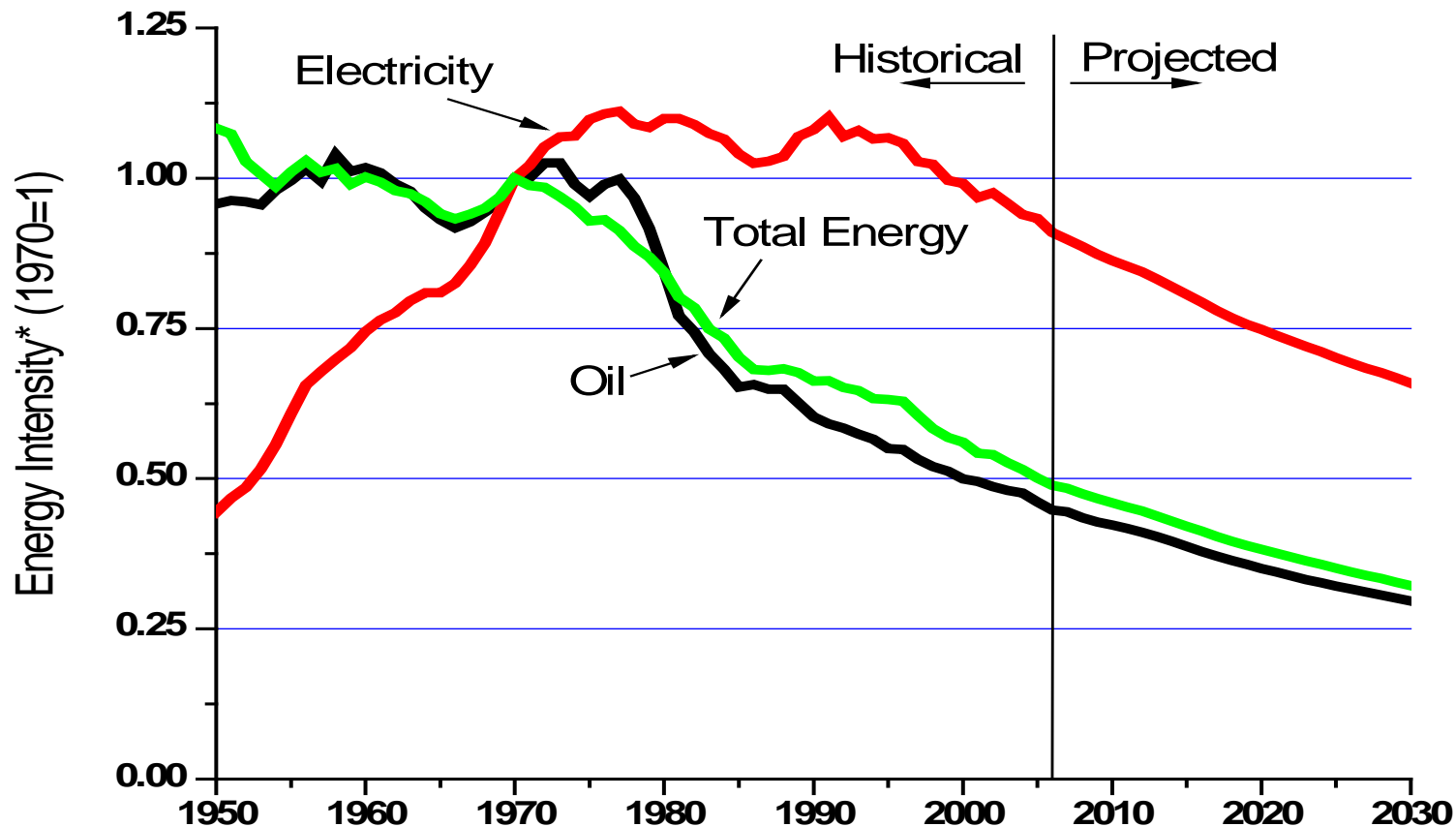
Potential for Increasing Energy Efficiency is Enormous

Potential Electricity Savings in Commercial and Residential Buildings in 2020 and 2030 (currently 73% of electricity used in US – space heating and cooling, water heating, and lighting)



Energy Intensity* (efficiency) of the U.S. Economy Relative to 1970 levels

*Energy consumed per dollar GDP



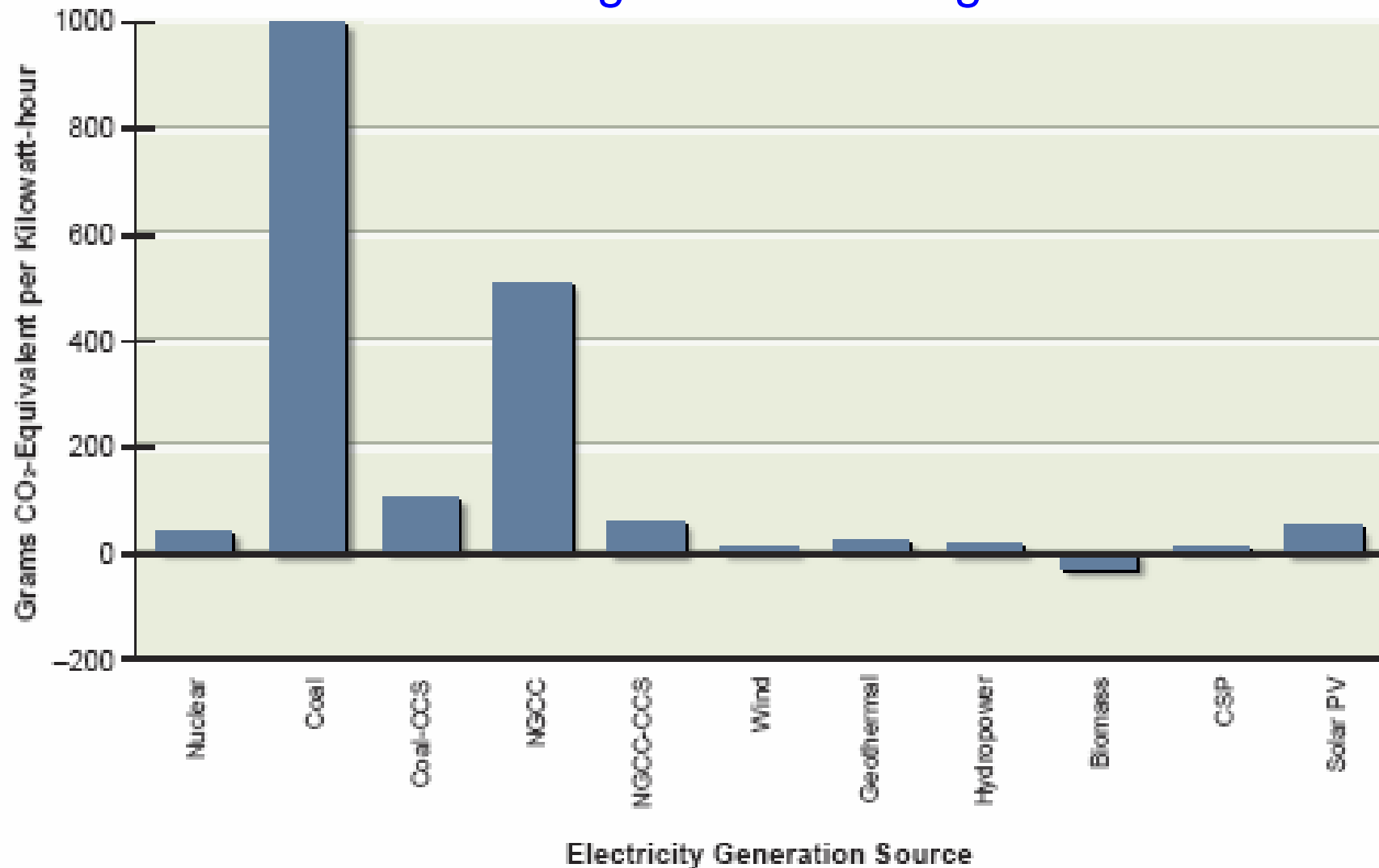
*Energy consumed per dollar GDP (2000 constant dollars)

Source: Based on EIA, 2006

Renewable Energy (Solar, Wind, Geothermal, Biomass, hydropower)

- Other Speakers will cover Renewable Energy – will make only a few remarks
- Renewable energy technologies, a critical element of the low-carbon pillar of global energy supply, are rapidly gaining ground, helped by global subsidies amounting to \$120 billion in 2013.
- Renewable energy sources – in power generation as well as transport –reached a record **3.0% of global energy consumption in 2014**, up from 0.9% a decade ago. Renewables accounted for a record **6.0% of global power** generation. The strong growth of renewables in many countries raises their expected share in global **power** generation to **~ 30% by 2040**.
- Cost and efficient energy storage remain as issues requiring innovative solutions. For example, the high cost of solar plus being intermittent source is not helping solar in some countries such as the US.
- **Renewables alone cannot meet the booming global population's insatiable appetite for energy in the long term.** The World needs Other Clean Energy Sources (e.g. **nuclear fission and fusion**) to meet growing energy demands and make the transition to a cleaner world by 2050

Estimated **Greenhouse Gas Emissions from Electricity Generation**
Nuclear and Renewable Energy Sources are essential to addressing Climate Change



Nuclear Fission

Current Contributions and Future Outlook

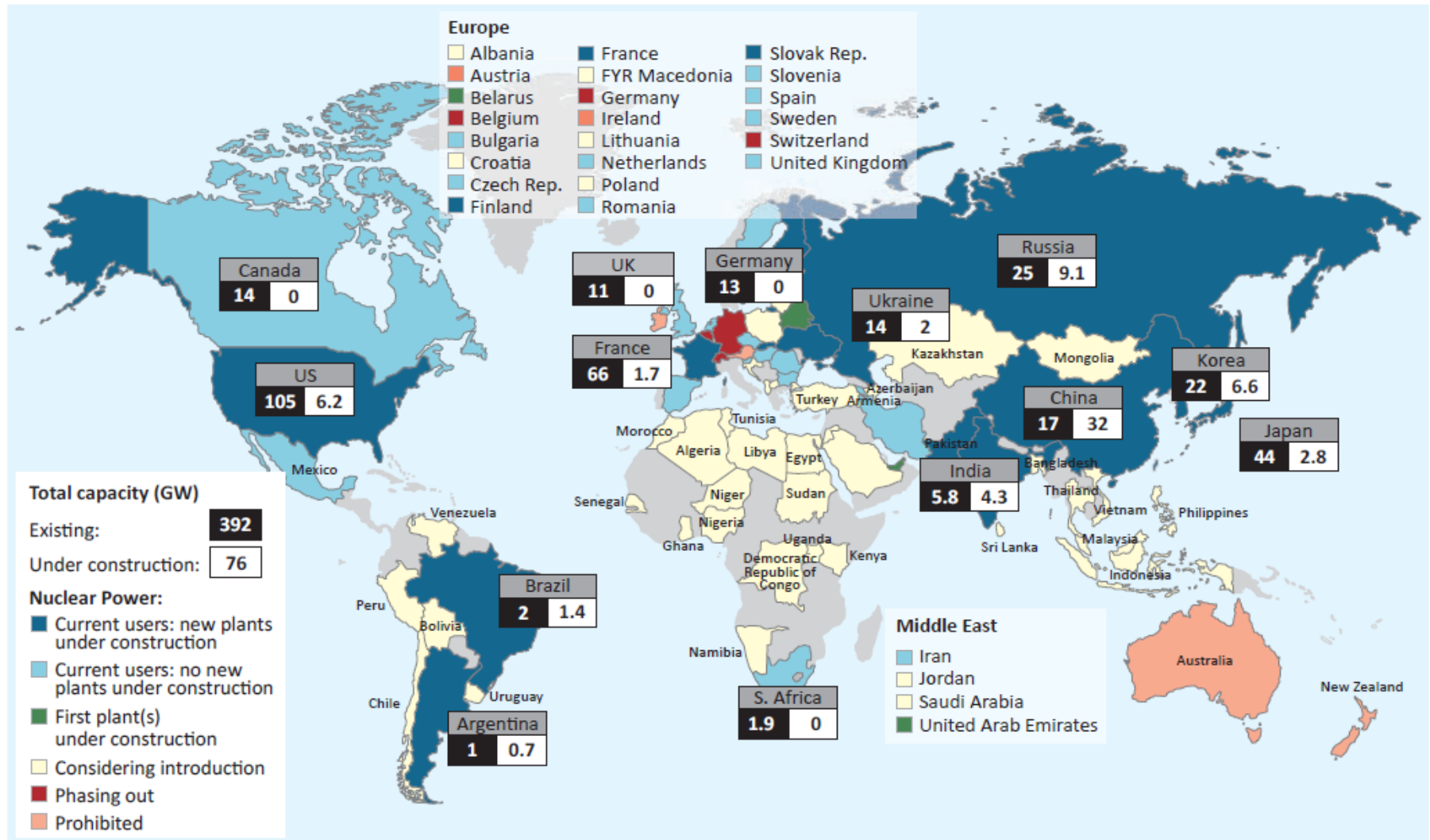
Internationally, there are ongoing plans for nuclear energy expansion (**Nuclear Renaissance**)

- **Worldwide Currently Operating:** 436 fission power reactors totaling 392 GWe of capacity in 31 countries (11% of world's electricity). Additionally, 67 more reactors with ~70 GWe currently under construction.
 - 357 of the 436 reactors are light-water reactors (LWRs). The rest are heavy-water reactors, gas cooled reactors, and graphite-moderated light-water reactors.
- **US** has currently 99 nuclear power plants. As of October 2015: 5 under construction
- **China** has the most aggressive nuclear energy plan
 - China's fast reactor plans
 - Present: 23.1 GWe
 - **2020: 58 GWe**
 - **2030: 150 Gwe**
 - Experimental: 20 MWe (2010)
 - Large: BN-800 (2018,suspended) and CDFR-1000 MWe (2023)

Source: world-nuclear.org

But managing nuclear materials and proliferation is becoming increasingly complex, requiring a modernized international approach.

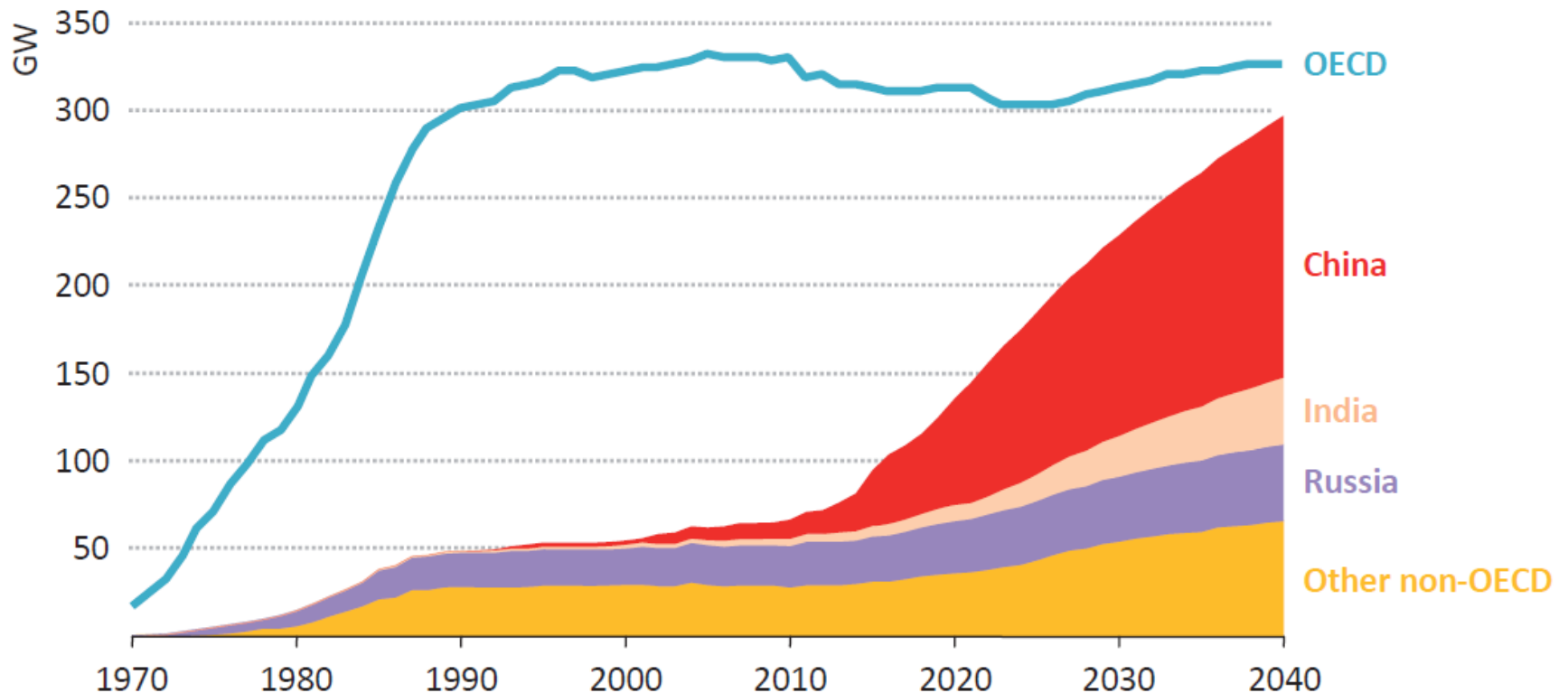
Global Status of Nuclear Power Plants at the end of 2013



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

WEO-2014

History of installed nuclear power capacity by key world region and future outlook based on IEA-WEO-2014 scenario



Impressive Improvements in Economics of Nuclear Power in Existing Fission Power Plants

- Incremental improvements enabled currently operating fission power plants to produce more energy than anticipated over their lifetimes. **The U.S. average plant capacity factor increased from 66% in 1990 to 91.7% in 2014.** Source: Nuclear Energy Institute

- From Australian National Affairs Article:

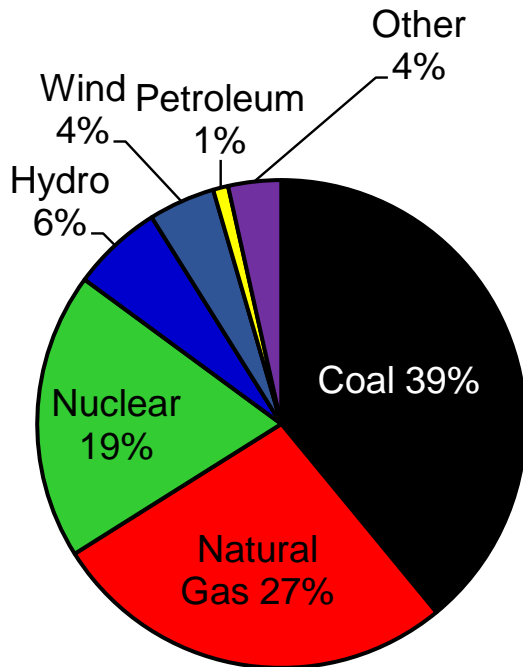
The standout technology, from a cost perspective, is nuclear power. From the eight nuclear cost studies we reviewed (all published in the past decade, and adjusted to 2009 dollars), the median cost of electricity from current technology nuclear plants was just above new coal plants with no carbon price. Having the lowest carbon emissions of all the fit-for-service technologies, **nuclear remains the cheapest solution at any carbon price. Importantly, it is the only fit-for-service baseload technology that can deliver the 2050 emission reduction targets.....**

- **Also, other improvements in safety and reduced generation of high level waste.**

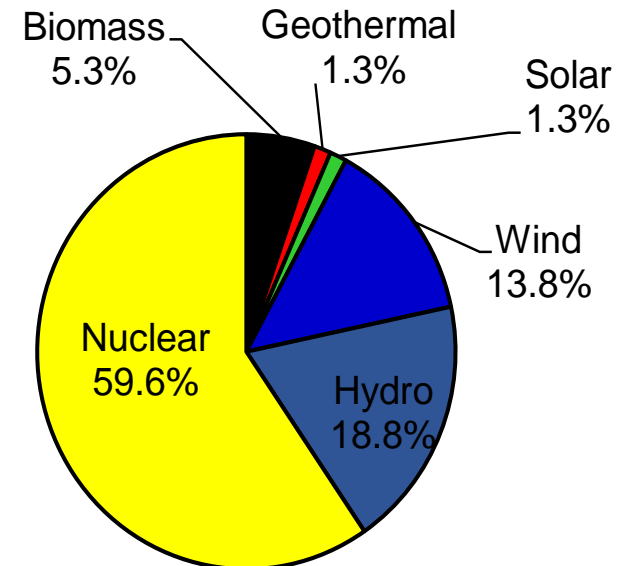
Nuclear Power Must Remain a KEY Part of Our Energy Portfolio

Nuclear is the third largest source of U.S. electricity

- 19 % of electricity generation
- 59 % of GHG emission-free electricity
- Nuclear electricity is 3 times more than Solar, Wind and Geothermal combined



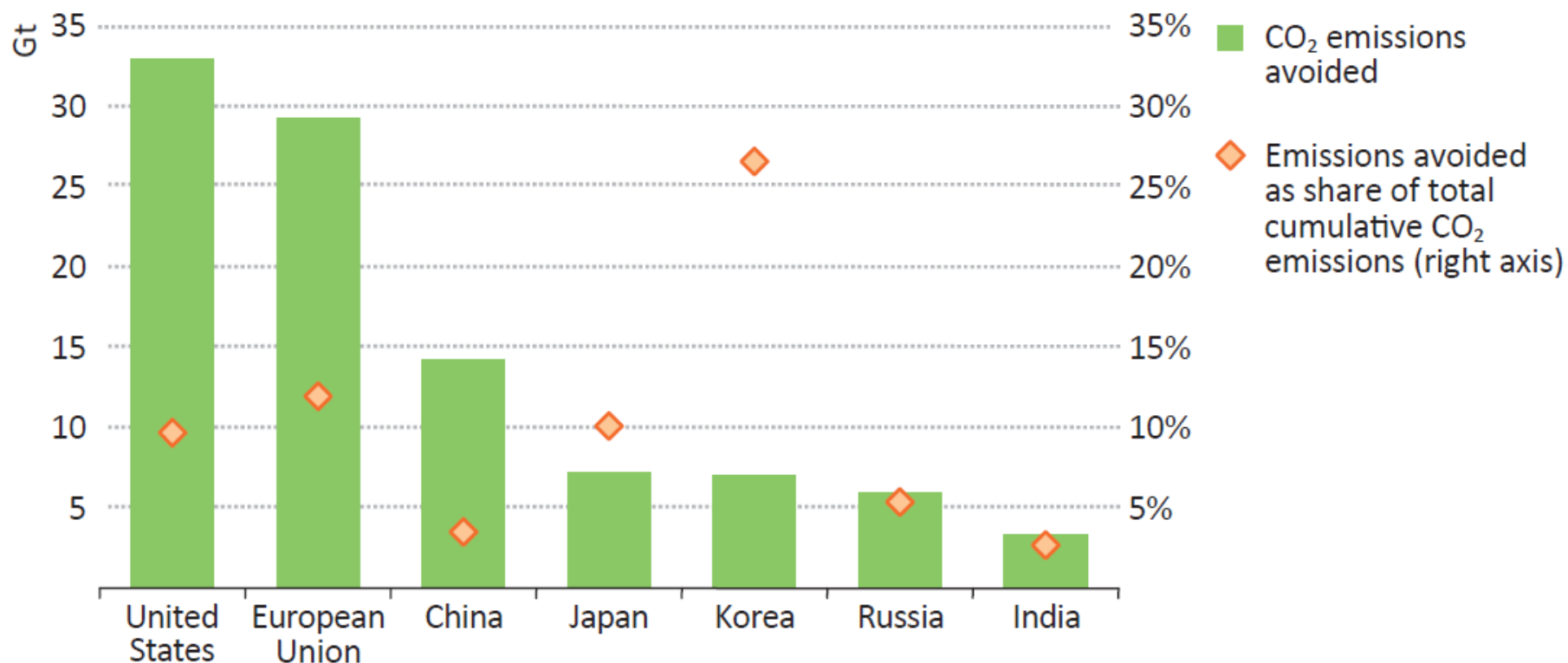
Nuclear energy is the dominant non-fossil energy technology



No GHG Electricity

Nuclear power **avoided** the release of over 56 Gt of CO₂ globally between 1971 and 2012. Cumulative global CO₂ emissions **avoided** by nuclear power are projected to climb to 111 Gt in the period 1971-2040.

Figure shows Cumulative CO₂ emissions **AVOIDED** by Nuclear Power in selected regions, 1971-2040 (IEA-WEO-2014 scenario)



Evolution of Nuclear Power

Generation I

Early Prototype Reactors



- Shippingport
- Dresden
- Fermi I
- Magnox

Generation II

Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- VVER/RBMK

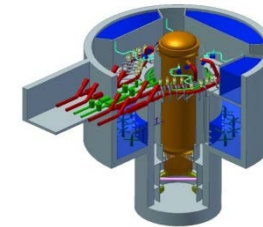
Generation III

Advanced LWRs



- ABWR
- System 80+
- AP600
- EPR

Generation III+

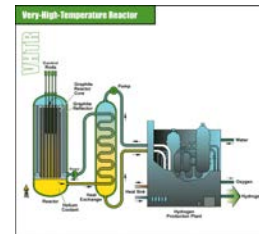


Near-Term Deployment

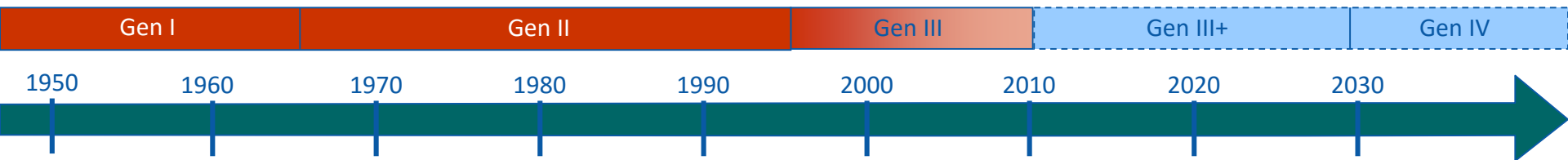
- AP1000
- PBMR
- SWR-1000
- ABWR-II

Evolutionary Improved Economics

Generation IV



- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

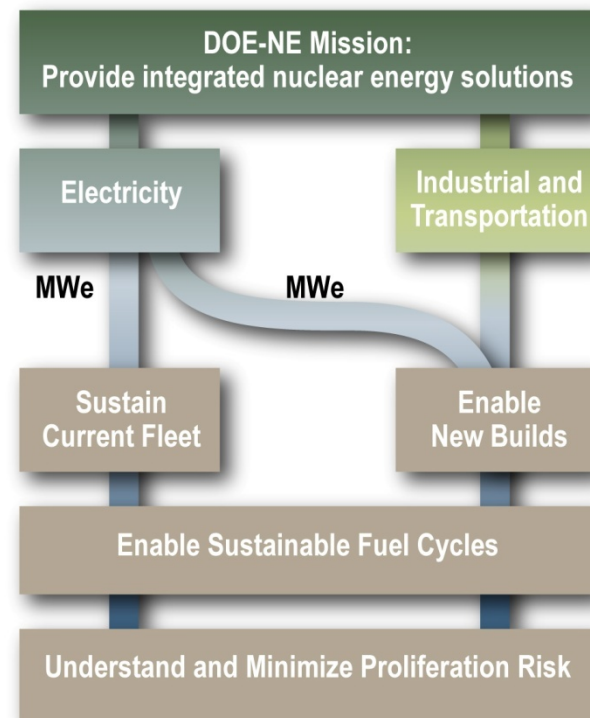


1. U.S. Department of Energy Gen-IV Roadmap Report



Current Nuclear Energy Research Objectives

- **Extend life of currently operating plants**
 - **Goal is to extend currently operating LWRs plant life from design life (40 years) to beyond 60 years**
- **Enable new builds for electricity and process heat production and improve the affordability of nuclear energy-**
 - Develop and demonstrate next generation advanced plant concepts and technologies
- **Enable sustainable fuel cycles**
 - high burnup fuel
 - Develop optimized systems that maximize energy production while minimizing waste
- **Understand and minimize proliferation risks**
 - Goal is limiting proliferation and security threats by protecting materials, facilities, sensitive technologies and expertise



NW10-013

CREATING a Star on Earth

Fusion: The Ultimate Energy Source for Humanity

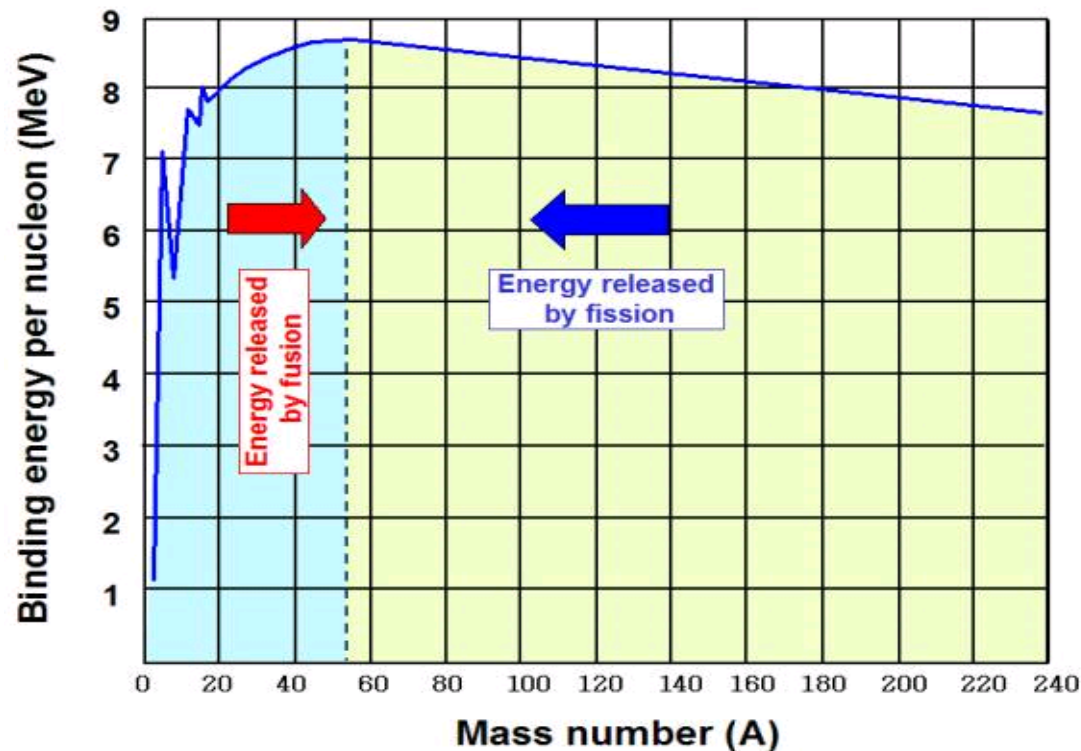
What is nuclear fusion?

- **Fusion powers the sun and stars:** Fusion is the energy-producing process taking place in the core of the sun and stars. Fusion research is akin to “creating a star on earth”
- **Two light nuclei combine to form a heavier nuclei, converting mass to energy** - the opposite of nuclear fission where heavy nuclei split
- **In nuclear (fission and fusion), mass is converted to energy , Einstein’s famous Eq.**

$$E = mc^2$$

Small mass → Huge energy

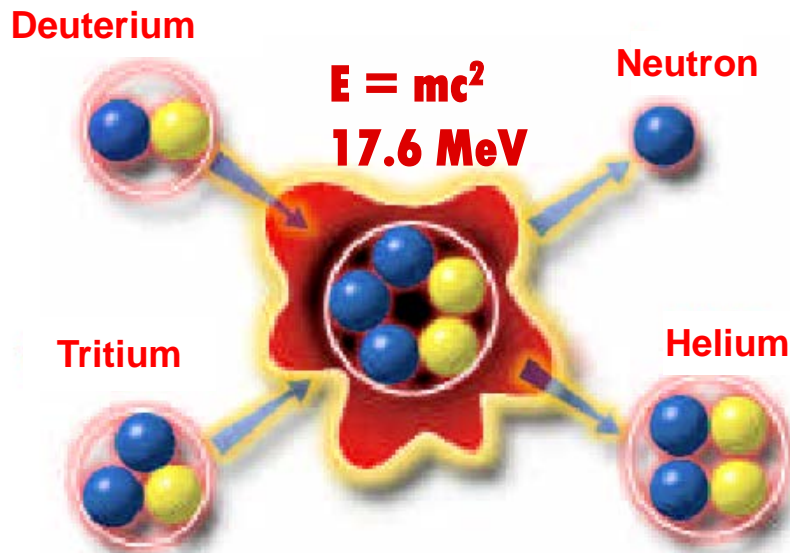
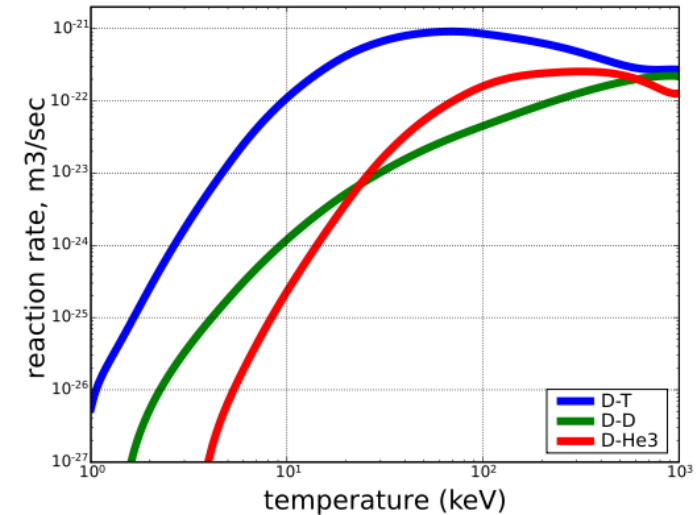
In contrast to fossil fuels (oil, gas, coal) where chemical energy is stored, and huge mass needed to “store” energy



A number of fusion reactions are possible based on the choice of the light nuclides

The World Program is focused on the Deuterium (D) - Tritium (T) Cycle

- D-T Cycle is the easiest to achieve: attainable at lower plasma temperature because it has the largest reaction rate and high Q value.



80% of energy release
(14.1 MeV)



Used to breed tritium and close the DT fuel cycle



Li in some form must be used in the fusion system

20% of energy release
(3.5 MeV)

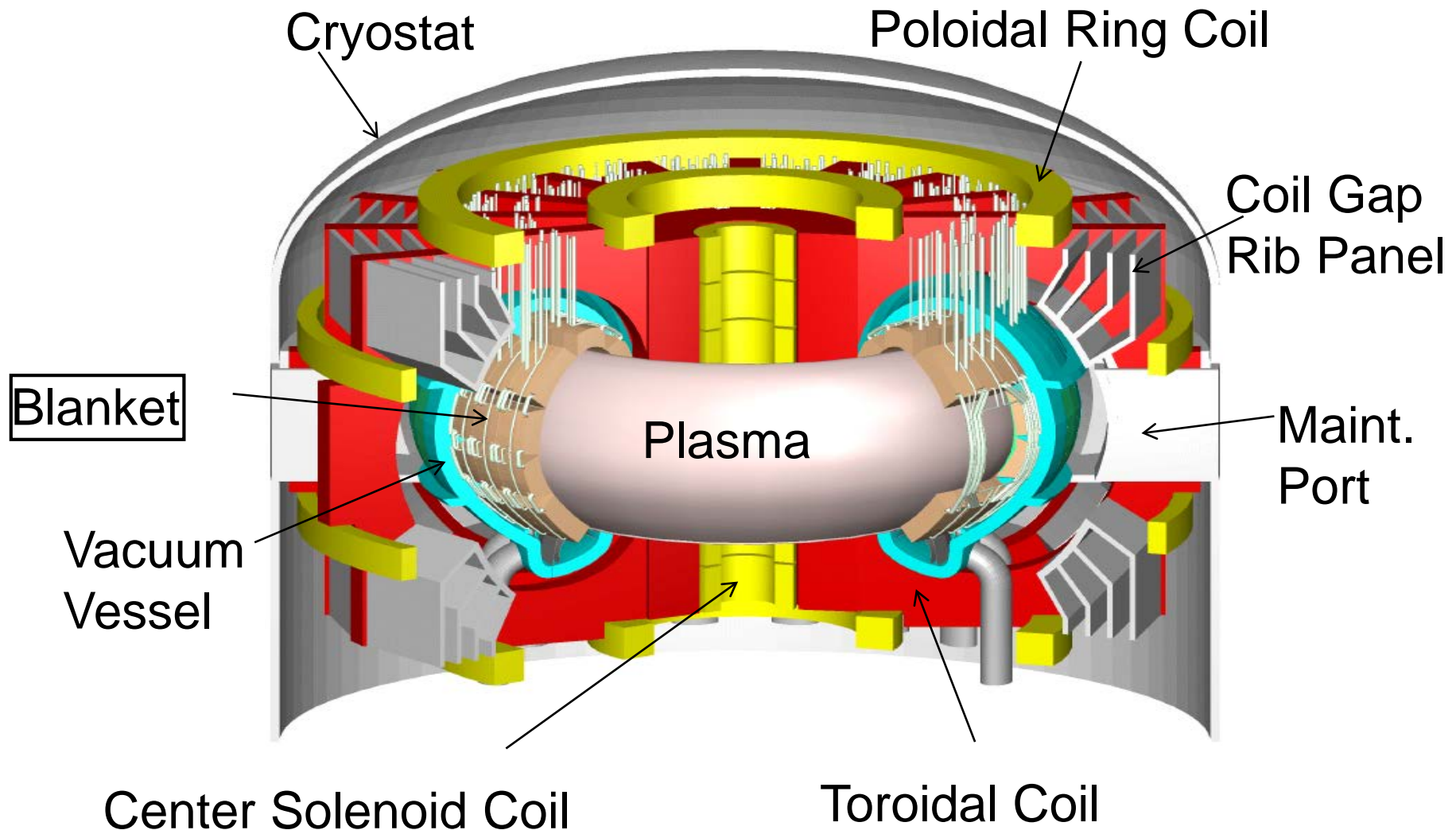
Incentives for Developing Fusion

- Sustainable energy source
(for DT cycle: provided that Breeding Blankets are successfully developed and tritium self-sufficiency conditions are satisfied)
- No emission of Greenhouse or other polluting gases
- No risk of a severe accident
- No long-lived radioactive waste

Fusion energy can be used to produce electricity and hydrogen, and for desalination.

The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2040(?)

Plans for DEMO are based on Tokamaks



(Illustration is from JAEA DEMO Design)

ITER

- The World has started construction of the **next step** in fusion development, a device called **ITER**.
- **ITER** will demonstrate the **scientific and technological feasibility** of fusion energy
- **ITER** will produce **500 MW** of fusion power.
- Cost is ~16 billion dollars.
- **ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea, and India. – represent half the world's population**
- ITER construction site is Cadarache, France
- ITER will begin operation in the early 2020's
- **ITER will open the way for commercial reactors**

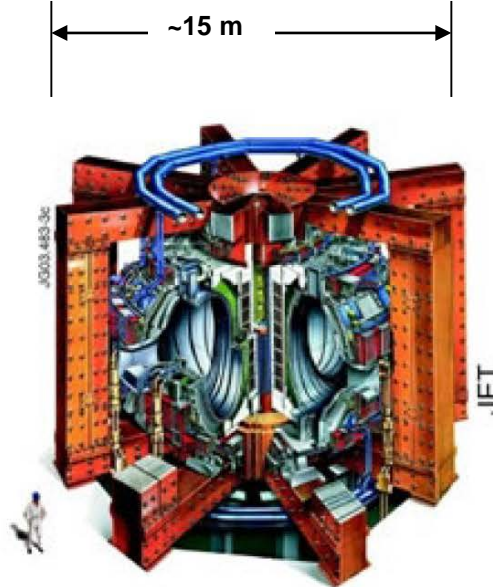
ITER is a reactor-grade tokamak plasma physics experiment – a huge step toward fusion energy

- Will use D-T and produce neutrons
- 500MW fusion power, $Q=10$
- Burn times of 400s
- Reactor scale dimensions
- Actively cooled PFCs
- Superconducting magnets

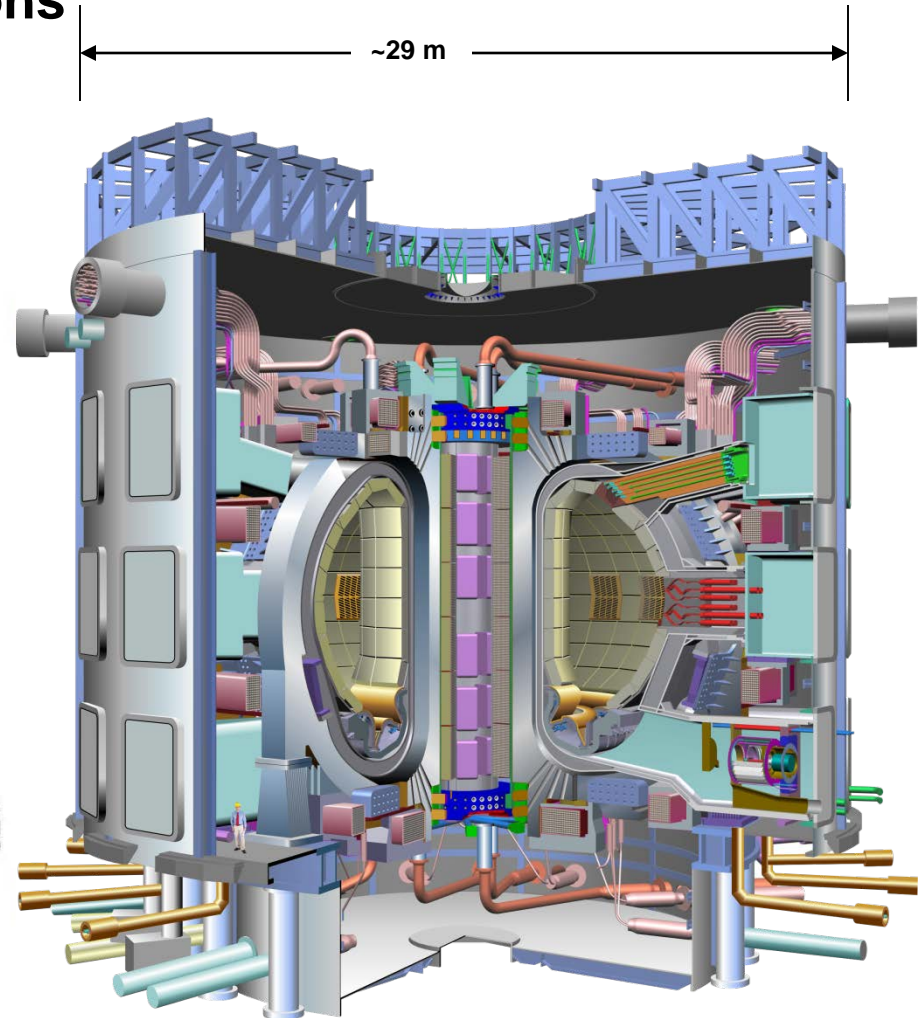
By Comparison

JET

- ~10 MW
- ~1 sec
- Passively Cooled



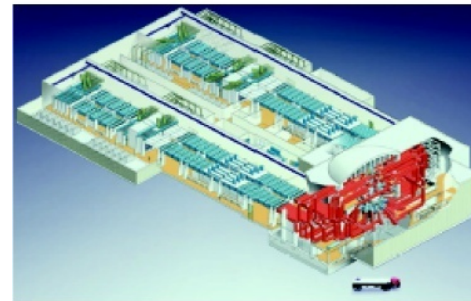
JET



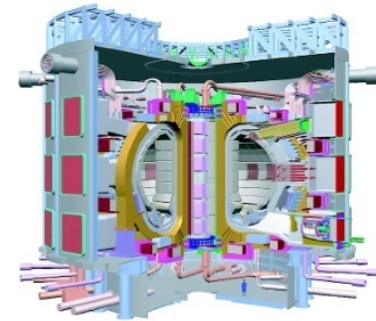
ITER

Fusion Research is about to transition from Plasma Physics to Fusion Nuclear Science and Engineering

- 1950-2015
 - The Physics of Plasmas
- 2015-2035
 - The Physics of Fusion
 - Fusion Plasmas-heated and sustained
 - $Q = (E_f / E_{\text{input}}) \sim 10$
 - ITER (MFE) and NIF (inertial fusion)
- ITER is a major step forward for fusion research. It will demonstrate:
 1. Reactor-grade plasma
 2. Plasma-support systems (S.C. magnets, fueling, heating)



National Ignition Facility



ITER

**But the most challenging phase of fusion development still lies ahead:
The Development of Fusion Nuclear Science and Technology**

The cost of R&D and the time to DEMO and commercialization of fusion energy will be determined largely by FNST.

Fusion Nuclear Science & Technology (FNST)

FNST is the science, engineering, technology and materials for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

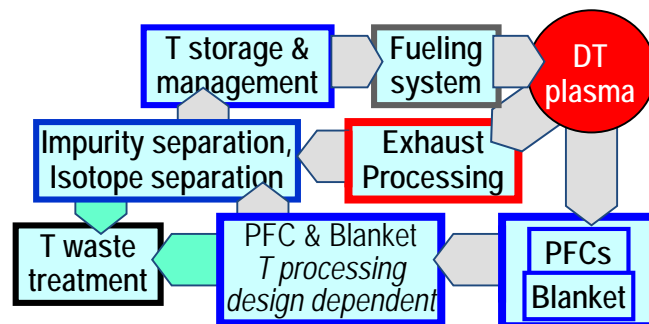
In-vessel Components (Core)

- Divertor/PFC
- Blanket and Integral First Wall
- Vacuum Vessel and Shield

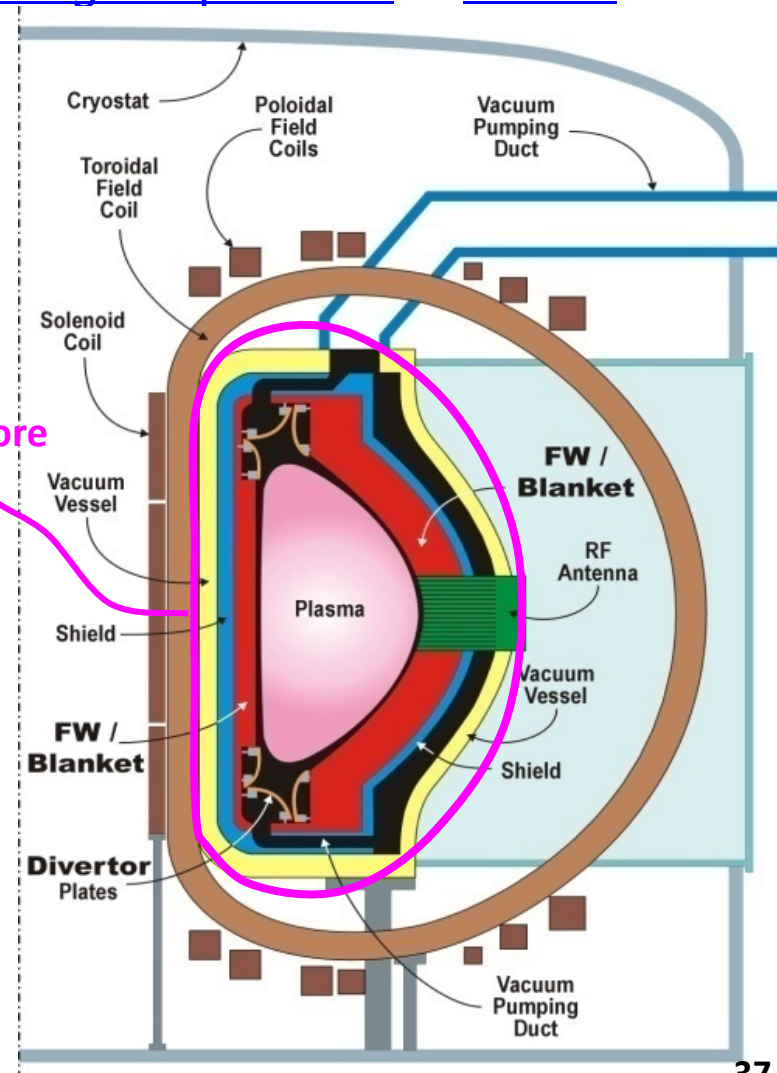
Key Supporting Systems

- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems

*Tritium Fuel Cycle
pervades entire
fusion system*

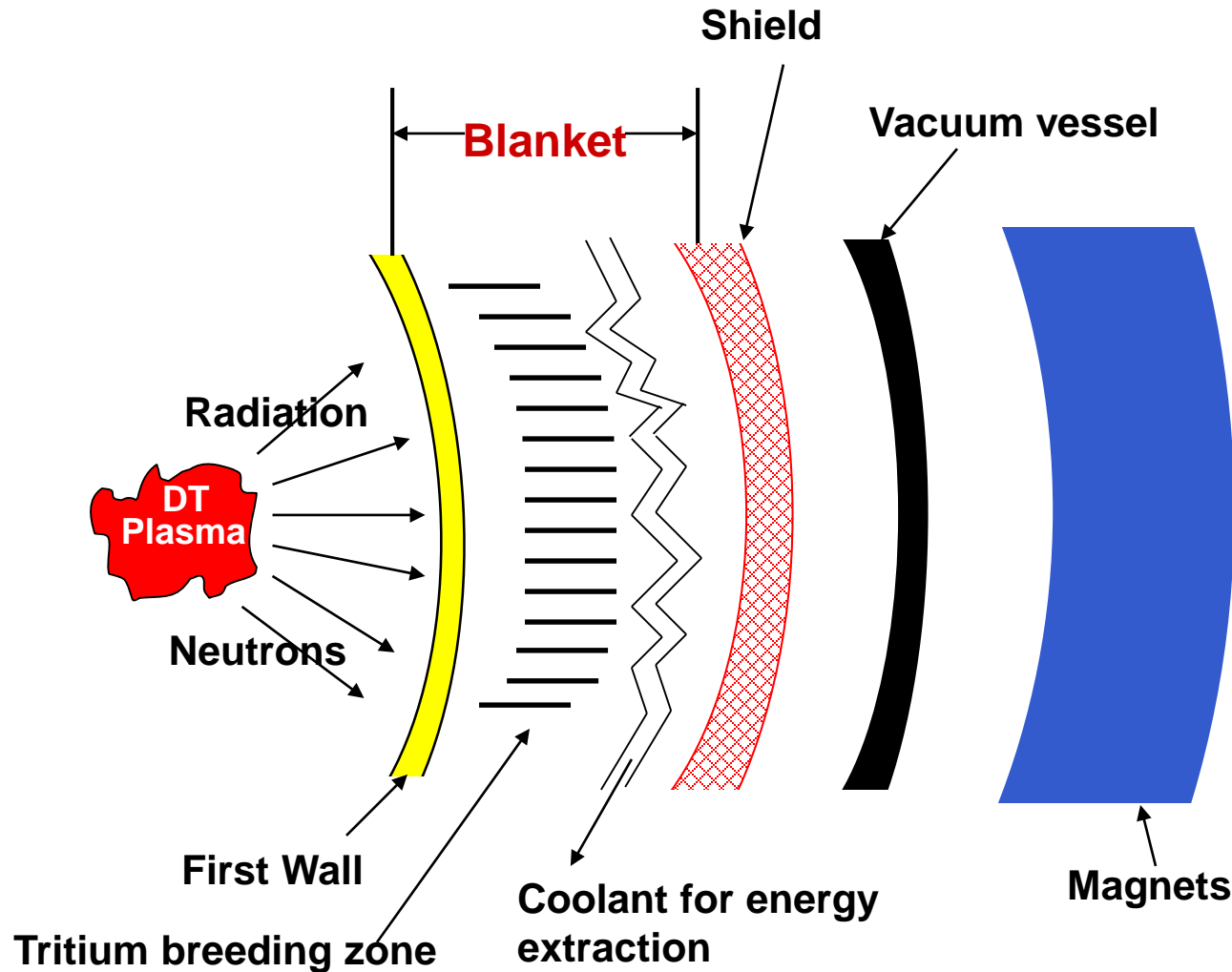


FNST Core



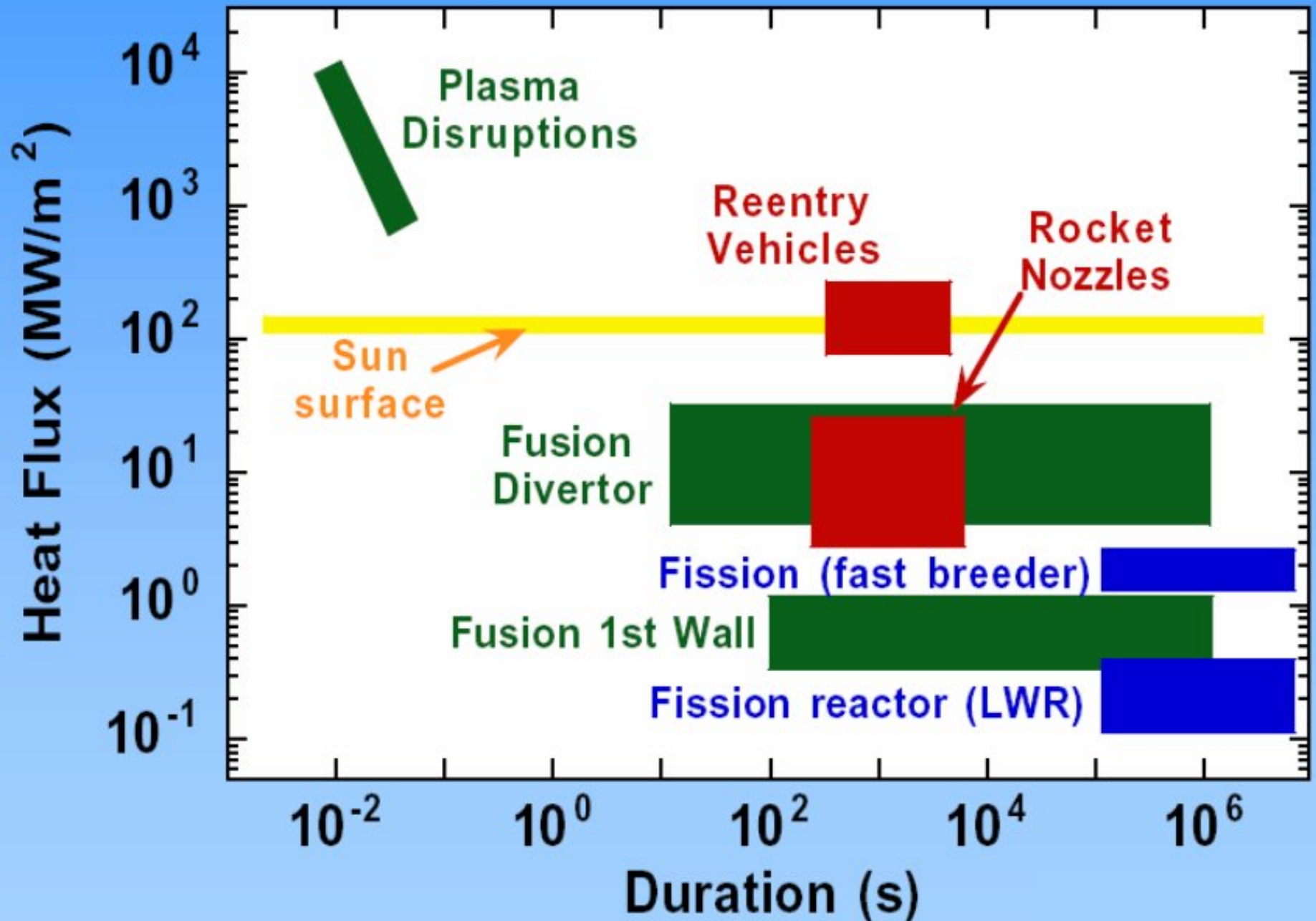
A Key FNST Component is the Blanket

The primary functions of the blanket are to provide for:
Power Extraction & Tritium Breeding



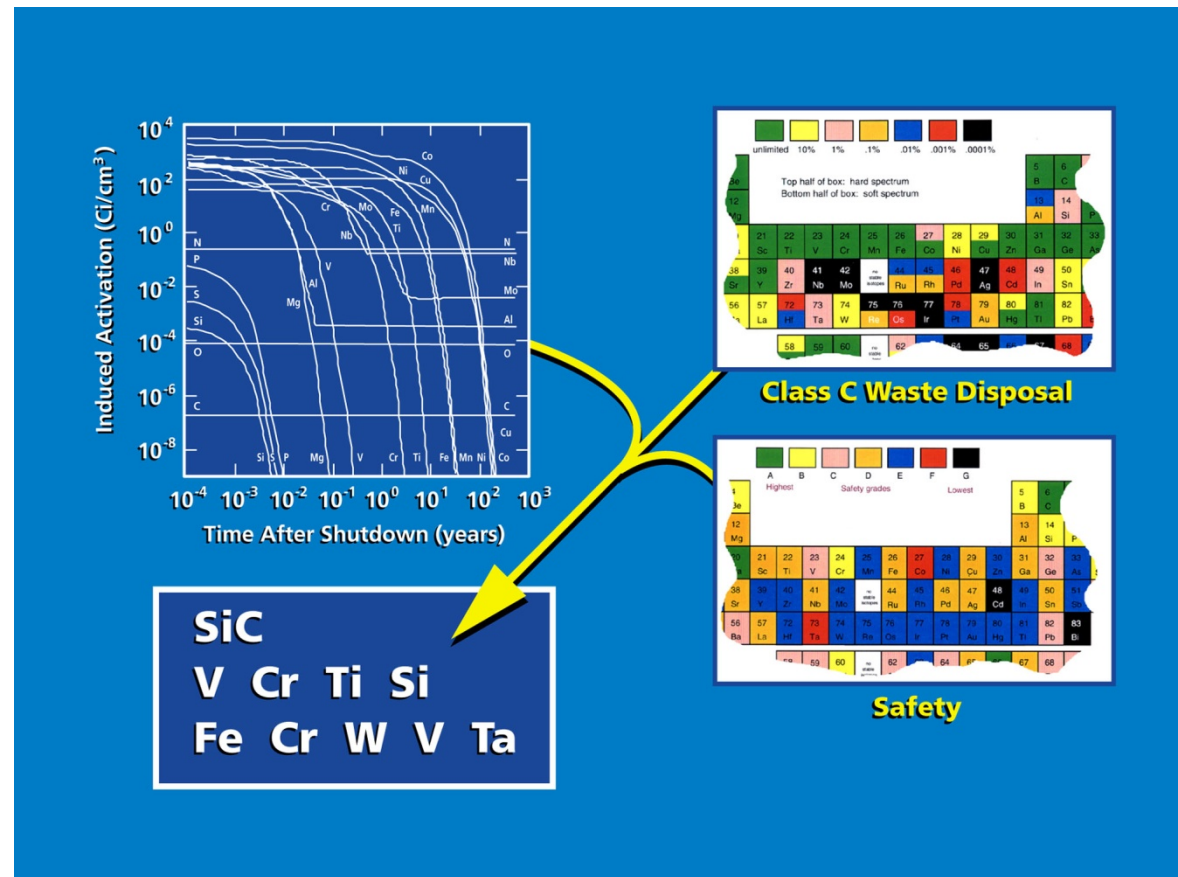
Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. He-cooled Li ceramics are also candidates.

Comparison of Heat Fluxes



In fusion, the fusion process does not produce radioactive products. Long-term radioactivity and waste disposal issues can be minimized by careful **SELECTION** of **MATERIALS**

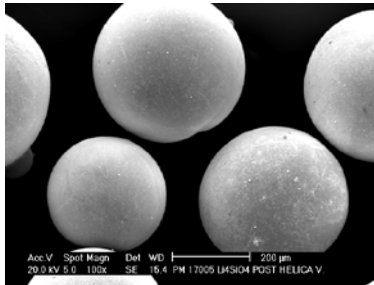
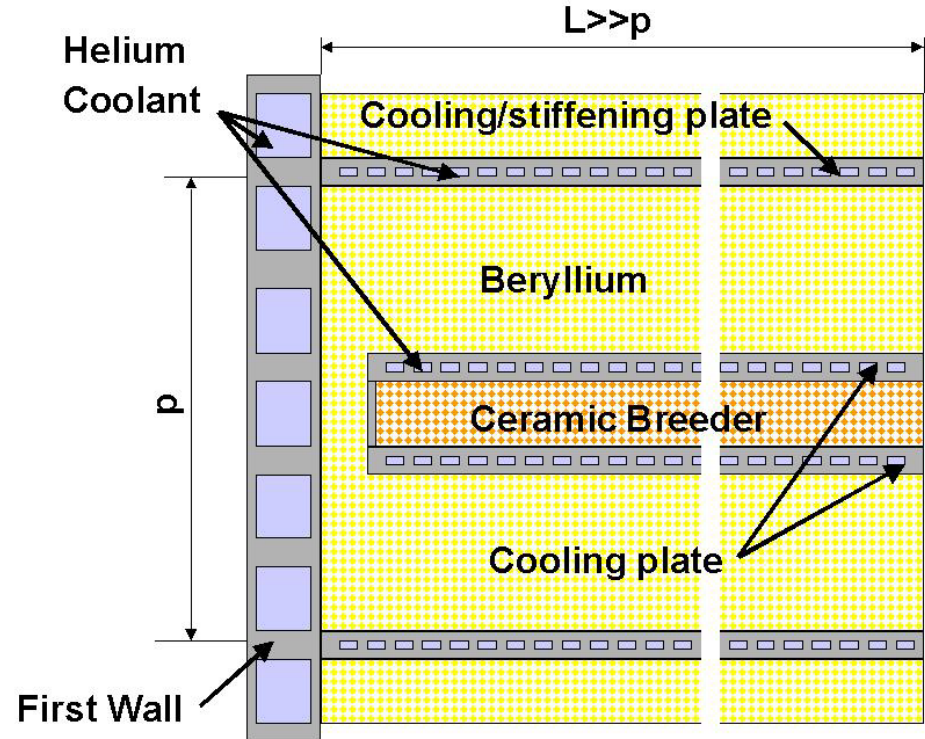
- This is in contrast to fission, where long term radioactivity and waste disposal issues are “intrinsic” because the products of fission are radioactive.
- Based on safety, waste disposal and performance considerations, the three leading candidates are:
 - RA FM and NFA steels
 - SiC composites
 - Tungsten alloys (for PFC)



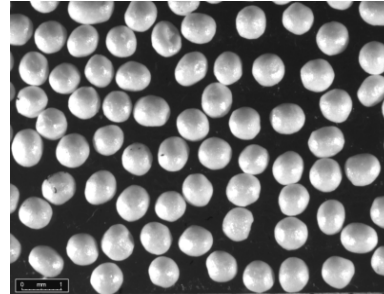
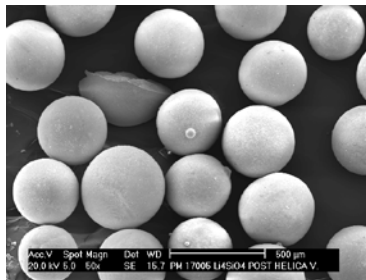
Solid breeder blankets utilize immobile lithium ceramic breeder and Be multiplier

Material Functions

- **Beryllium** (pebble bed) for neutron multiplication
- **Ceramic breeder**(Li_4SiO_4 , Li_2TiO_3 , Li_2O , etc.) for tritium breeding
- **Helium purge** to remove tritium through the “interconnected porosity” in ceramic breeder
- **High pressure Helium** cooling in structure (advanced ferritic)



0.2- 0.4 mm Li_4SiO_4 pebbles (FZK)



0.6 – 0.8 mm Li_2TiO_3 pebbles (CEA)



NGK Be-pebble

Flows of electrically conducting coolants will experience complicated **MHD** effects in the magnetic fusion environment

3-component magnetic field and complex geometry

- Motion of a conductor in a magnetic field produces an EMF that can **induce current** in the liquid. This must be added to Ohm's law:

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$

- Any induced current in the liquid results in an additional **body force** in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{V} + \mathbf{g} + \frac{1}{\rho} \mathbf{j} \times \mathbf{B}$$

- For **liquid metal coolant**, this body force can have dramatic impact on the flow: e.g. **enormous MHD drag**, highly distorted velocity profiles, non-uniform flow distribution, modified or suppressed turbulent fluctuations.

Dominant impact on LM design.

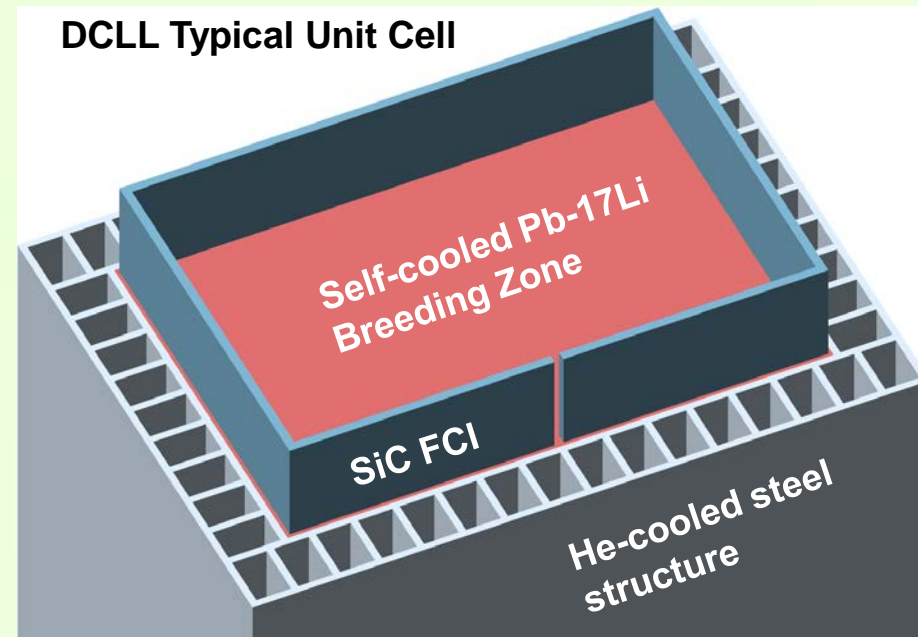
Challenging Numerical/Computational/Experimental Issues

Pathway Toward Higher Temperature through Innovative Designs with Current Structural Material (Ferritic Steel):

Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept

- ❑ First wall and ferritic steel structure cooled with helium
- ❑ Breeding zone is self-cooled
- ❑ Structure and Breeding zone are separated by SiCf/SiC composite *flow channel inserts (FCIs)* that:
 - ❖ Provide thermal insulation to decouple PbLi bulk flow temperature from ferritic steel wall
 - ❖ Provide electrical insulation to reduce MHD pressure drop in the flowing breeding zone

FCI does not serve structural function



Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure \Rightarrow High Efficiency

**The problem with fusion is that it is not being developed fast enough (taking too long!)
“The Time to Fusion seems to be always 40 years away”**

The World Needs Fusion.

To accelerate the development of fusion energy requires a change in Governments Policies and in the Fusion Community strategy/focus:

- **Need More Substantial Funding : Governments must invest in long-term solutions for the future**
- **Problems are challenging: Need More Ingenuity**
- **Fusion Community strategy/focus need to change: Need to Focus on the Major Remaining Challenge: Launch an aggressive FNST Program NOW**

**This is essential to realizing fusion by
the middle of the 21st Century**

Closing Remarks

- Energy plays a critical role in economic development, economic prosperity, national security, and environmental quality
- Solving the Energy Problem and Reducing Greenhouse Gas Emission Requires Pursuing a Diversified Portfolio Approach
- **Key Major Transformations required:**
 - **Efficient use of energy**, e.g., buildings (lighting, heating and cooling), cars and trucks, and industry.
 - **New sources of energy for producing electricity** that reduce emissions of CO₂—nuclear, fusion, coal with CO₂ removed and stored, solar, wind, and geothermal.
 - **Transportation fuels** that derive from alternatives to petroleum, e.g., liquids from biomass, coal and electricity.

Closing Remarks (cont'd)

- **Fusion is the most promising long-term energy option**
 - Renewable fuel, no emission of greenhouse gases, no long-term radioactive waste, inherent safety
- But the problem is that fusion is not being developed fast enough. **“The Time to Fusion seems to be always 40 years away”**. **Need more funding, more ingenuity, and focus on the most difficult remaining challenge : Fusion Nuclear Science and Technology (FNST)**

Fusion research requires the talents of many scientists and engineers in many technical disciplines. Need to attract and train bright young students and researchers.

For References and Additional Reading:

1. Abdou's presentations and publications on:
(<http://www.fusion.ucla.edu/abdou/>)
2. UCLA Energy Center (<http://cestar.seas.ucla.edu/>)
3. CEREL (<http://ncseonline.org/cerel/>)
4. Additional Information on the America's Energy Future Effort:
(<http://www.nationalacademies.org/energy>)
5. *John P. Holdren, Assistant to the (US) President for Science and Technology, OSTP:*
<http://www.whitehouse.gov/administration/eop/ostp>
6. IEA World Energy Outlook 2014 ISBN: 978-92-64-20805-6
7. British Petroleum Statistical Review of World Energy

Thank You!